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OBSERVATIONS OF DISTANT EARTHQUAKES[1].

BY F. OMORI.

The earthquake motion consists in general of several sets of vibrations, whose amplitude and period range within wide limits. We shall find it convenient to divide the motion into two classes: the *Sensible* or *Macro-Seismic,* namely that which can be felt as tremblings or shocks; and the *Insensible* or *Micro-Seismic,* namely that which cannot be felt. In the former, quick vibrations co-exist with slower ones, while in the latter quick vibrations are either absent or extremely minute. Some of the vibrations in the insensible motion are as large as, or even larger than, the vibration in small but sensible local earthquakes; they are insensible only because their period is very long and consequently their acceleration small; the lowest limit of the "intensity" or acceleration of the sensible motion being about 17^{mm} per second. The quick period and short length waves in the earthquake motion are dissipated, with the increase of the distance from the center of disturbance, more rapidly than the slow, and long waves; the result being that the motion due to a distant earthquake is simpler in character than that due to a near one, and is entirely micro-seismic or insensible. A "distant earthquake" may here be taken as denoting a seismic disturbance, whose epi-central distance from a given station is over some 2000^{km} or 1500 miles.

The Earth's crust being regarded as an elastic medium through which seismic waves are propagated, the investigation of these waves, of their mode of propagation, and their behavior under various circumstances form a very important branch of the physics of the Earth, and especially the observations of distant earthquakes lead to several interesting results, which may help the solution of some of the important problems relating to the condition of the Earth's interior. By means of modern seismographs, which are very sensitive, we can observe a great earthquake in any part of the world, the motion due to such a disturbance lasting generally from 1 to 5 hours.

NEAR EARTHQUAKES. For the sake of reference, I shall state briefly the character of an ordinary or sensible earthquake disturbance. Such a motion, as observed with a seismograph, begins always with vibrations of small amplitude and comparatively short period. These are known as the *preliminary tremors* and last from a few seconds to a few

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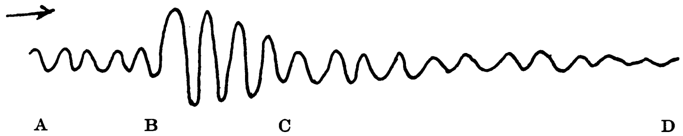
[1] Read at the meeting of the Society, June 9, 1906.

Diagrammatic Representation Of The Earthquake Motion



AB—Preliminary tremor. BC—Principal portion. CD—End portion.

minutes; next come those of large amplitude, constituting the principal and most active part; and finally the earthquake ends with feeble movements, which may be called the *end portion.* When the origin of the disturbance is near to the observer, a rumbling sound like that of distant thunder, or a rushing sound like a blast of wind is heard just before the arrival of the tremblings of the ground. These sound phenomena, which are of frequent occurrence in a rocky district, but very rare at places situated in plains, are probably due to the rapid vibrations existing in the *preliminary tremor.* The well-known fact that some animals often show signs of disquietude just before an earthquake, is probably due to their having an acute feeling and being alarmed at the first movements of the preliminary tremor. The duration of the preliminary tremor does not depend on the magnitude of the earthquake, but is found to vary with radial distance. Thus if Y denote the duration of the preliminary tremors of an earthquake, at a place, whose distance from the origin of disturbance is X, we have the following empirical equation:

$$X^{km} = 7.27Y^{sec} + 38^{km}$$

which is to be used for values of X between 100 and 1000 km. This equation is very useful and enables us to estimate, from the diagram taken at any station by a sufficiently sensitive seismograph, the distance of the earthquake origin. Or, if the seismograph records be simultaneously taken at two or more stations, we can easily fix the approximate position of the origin. As an example, I refer to the excellent Ewing seismograph record* taken by Dr. Campbell at the Lick Observatory of the great earthquake of April 18th, last. According to that seismogram, the preliminary tremor lasted about 10 to 12 seconds, from which it may be inferred that the most central part of the great disturbance was at a distance of about 130^{km}, or some 80 to 90 miles, from Mount Hamilton.

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*See illustration facing page 212.

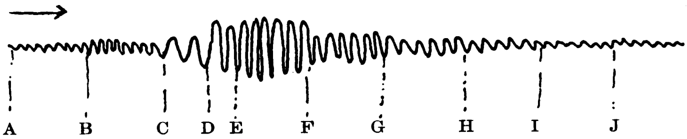
The duration of the strongest part in the principal portion in destructive earthquakes, which varies generally between 4 and 10 seconds, reaches, in case of extensive disturbance, some 30 seconds. From the Lick Observatory seismogram above mentioned, the duration of the principal portion in the recent great shaking seems to have been about 40 seconds.

In slight earthquakes, the movement of the ground is small, being a mere fraction of a tenth of an inch. When the motion reaches some one-half inch, the earthquake becomes strong and may cause slight damage. When, further, the motion reaches a few inches, the earthquake is destructive, and ordinary brick houses, chimneys, etc., will be considerably damaged. The motion in the strongly shaken parts of San Francisco in the recent earthquake, was probably 3 inches.

In ordinary cases, the vertical component of the earthquake motion is much smaller than the horizontal, being, even when very great, unable by itself to produce any great damage. In fact, with respect to the destructive power of the earthquake motion, the vertical component is only of secondary importance in comparison with the horizontal; in other words, the seismic damage to structures may, excepting the cases of sinking of foundations or collapsing of thin and weak vaults, be regarded as due to the horizontal motion.

DISTANT EARTHQUAKES. A careful examination of seismograms shows that the earthquake motion consists generally of several phases or sections, in each of which the period remains essentially constant, while the amplitude is also on the whole constant, except for the occurrence of maximum and minimum groups.

DIAGRAMMATIC REPRESENTATION OF THE EARTHQUAKE MOTION PROCEEDING FROM A DISTANT ORIGIN.



AB—1st preliminary tremors.
BC—2nd preliminary tremors.
CD—1st phase of the principal portion.
DE—2nd phase of the principal portion.
EF—3rd phase of the principal portion
FG—4th phase of the principal portion.
....
J—End portion.

The successive phases of the earthquake motion, illustrated in the figure, are as follows:

The *preliminary tremor,* which consists of vibrations of small amplitude and of comparatively short period, is divided into the earlier portion or the *first preliminary tremor,* and the later portion or the *second preliminary tremor.* Commencement of the latter is marked by an increase of the amplitude, and, in many cases, also by the appearance of slow undulations.

The *principal portion* denotes the most active part of an earthquake which follows the preliminary tremors and consists of movements of larger amplitude. The earlier part of the principal portions is further subdivided into three successive stages as follows: (a) the *first phase,* consisting of a few very slow movements; (b) the *second phase,* consisting of slow movements, whose period is generally somewhat shorter than in the first phase; (c) the *third phase,* consisting of vibrations of a period much quicker than that in the preceding two phases. The third phase is followed by others of smaller amplitude. (FG, GH, etc.,) which may be termed respectively the fourth, fifth, sixth,. . .phases of the principal portion.

Lastly, the *end portion* denotes the feeble finishing part of earthquake motion, which follows the principal portion.

In earthquakes of near origin, the motion is, on account of the existence of quick vibrations of macro-seismic character, much more complex than in distant earthquakes, it being generally difficult to subdivide the principal portion into the different phases.

As in the case of near earthquakes, the *duration* of the preliminary tremors at a given place is found to depend on the distance of the origin; thus let X denote the actual distance between the epicenter and the observing place, and Y the total duration of the first and second preliminary tremors, then we have the following empirical relation:

$$X^{km} = 6.54\ Y^{sec} + 720^{km}$$

which has been deduced from the observation of different earthquakes, whose X varied between 2000 and $14{,}000^{km}$. Again, if Y_1 denote the duration of the first preliminary tremor, X having the same signification as before, we get the following formula:

$$X^{km} = 17.1^{sec}\ Y_1 - 1360^{km}$$

Each of these equations may be used for determining at once the distance of an unknown earthquake from the record taken at any given place.

The time $(= T_0)$ of occurrence at the origin of any distant earthquake may approximately be calculated, from the seismographical record, by the following empirical formula:

$$T_0 = T - 1.165\ Y_1$$

where Y_1 has the same meaning as before, and T denotes the time of earthquake occurrence observed at a given place.

PULSATORY OSCILLATIONS. Before going further, let me refer to a phenomenon called "pulsatory oscillations." These are small slow pulse-like movements which are not of the earthquake origin; the ground being more or less in a state of vibration even when there is no earthquake at all. In some pronounced storms of pulsatory oscillations, the motion is quite as large as in small earthquakes; the maximum amplitude in each component being sometimes nearly 0.2^{mm}. Again, the horizontal motion is, in general, much greater than the vertical, although, in some cases, the latter is very marked and nearly equal to the former. The pulsatory oscillations, which may last for several days, do not indicate any succession of different phases as in the case of a great distant earthquake, although they are subject to alterations of maximum and minimum groups. As the period of pulsatory oscillations varies little, and remains constant for several successive hours, it may be supposed that these movements represent the proper vibrations of certain portions of the Earth's crust, such for instance as the plain of Musashi on which Tokio is situated. In fact, the different portions of the Earth's crust are continually executing greater or less movements, and the period of some of these vibrations ought to be determinable in each case from the geotectonic circumstances of the locality.

A careful examination of the horizontal pendulum diagrams obtained in Tokio shows that the pulsatory oscillations consist, in most cases essentially of vibrations with a period of about 4 seconds, more or less mixed up with those of a period of about 8 seconds. The vibrations of 4 seconds period occur very frequently, but cases are not wanting, where the vibrations of the 8 seconds period predominate almost exclusively. Again, there are sometimes cases in which the two kinds of vibrations occur in different parts of one and the same diagram. The average values of the periods of these two series of vibrations are respectively 4.4 sec. ($= Q_1$) and 8.0 sec. ($= Q_2$). We may perhaps assume that the 8 seconds period vibration constitutes the fundamental oscillation proper to the Tokio plain, the 4 seconds period being one of its harmonics.

The average period of the principal pulsatory oscillations at Osaka, Formosa, Göttingen, and some other places, is either nearly 4 seconds or nearly 8 seconds. It may be that the period (or periods) of the pulsatory oscillations is approximately constant all over the world.

Pulsatory oscillations generally accompany a cyclone; the effect of a great atmospheric depression being already sensible at a distance of some thousand kilometers. In a few cases, however, pronounced storms of pulsatory oscillations occurred on days when very quiet weather prevailed all over Japan.

In Tokio, earthquakes occur rather rarely, while pulsatory oscillations are going on actively. On the other hand, there are often local shocks when these oscillations come to a state of minimum activity.

PERIODS OF EARTHQUAKE VIBRATIONS. The predominating periods in the different phases of the distant earthquake motion observed at *Hitotsubashi* (Tokio) were as follows; those very frequently occurring being given in black letters.

	sec.	sec.	sec.	
1st preliminary tremors......	1.04	**4.6**	**8.7**	
2nd " "	**8.5**	14.8		
3rd section	22.9	27.6		
4th "	13.6	17.8	22.3	25.9
5th "	**9.3**	13.6		
Tail	**9.6**	16.0		

It will be observed that the two periods of about 4.5 and 8.5 sec. occur most frequently in the preliminary tremors; this being also the case with the observations at Hongo (University.)

Thus there are, in the first and second preliminary tremors, two predominating periods, which may be denoted by P_1 and P_2 and whose mean values are

$$P_1 = 4.6 \text{ sec.}, \ P_2 = 8.3 \text{ sec.}$$

Now these are practically identical respectively with the two periods, Q = 4.4 sec. and Q_2 = 8.0 sec., found for the pulsatory oscillation in Tokio. Moreover the periods P_1 and P_2 do not depend on the distance of an epicenter from the observing station, or on the nature of the disturbance at the seismic origin, but are characteristic of the region about Tokio. A similar conclusion probably holds good also for the periods in other stages of the earthquake motion. The conclusion is that the principal vibrations in the preliminary tremors of distant earthquakes and pulsatory oscillations are identical phenomena. The existence of P_1 and P_2 vibrations in the principal portion of the distant earthquake motion has been confirmed by the recent earthquake observations made in Formosa, and also by the observations in Tokio of the great Indian earthquake of April 4th, 1905.

We may probably explain the existence of the preliminary tremors somewhat as follows: The waves of the preliminary tremors are transmitted along a deep layer of the Earth's crust with a velocity of some 14^{km} of which I shall speak presently, and communicate a sort of stress to the superincumbent surface layer of the Earth's crust in the region about the observing station; the latter being, in consequence, thrown into its own proper vibrations. In fact, the preliminary tremors seem to be nothing else than the pulsatory oscillations, caused by the waves transmitted along a deep layer of the Earth's crust from the origin of earthquakes.

Taking the observations of great distant earthquakes, predominating periods in the different phases of the motion were found to be as follows:

	sec.	sec.	sec.
1st preliminary tremors	4.1	7.8	13.9
2nd “ “	4.8	8.2	15.0
Principal Portion, 1st phase	36.1		
“ “ 2nd phase	27.5	33.7	
“ “ 3rd phase	20.4	24.0	
“ “ 4th phase	11.7	14.9	
“ “ 5th phase	14.3		
“ “ 6th phase	14.5		
End Portion	9.9	14.3	19.8

The durations of the different phases of the earthquake motion are roughly equal to one another; the first and second phases of the principal portion being taken together.

The amplitude of motion is smallest in the first preliminary tremors, and greatest in the second and third phases of the principal portion.

The mean relative maximum amplitudes in the first and second preliminary tremors and in the successive phases of the principal portion were as follows:

	mm.
First preliminary tremor	100
Second preliminary tremor	560
First phase, principal portion	550
Second phase, principal portion	1820
Third phase, principal portion	1220
Fourth phase, principal portion	840
Fifth phase, principal portion	560
Sixth phase, principal portion	430

THE VELOCITIES OF PROPAGATION OF THE VIBRATIONS. In calculating the velocities of propagation of distant earthquake waves, it makes a great difference according as we suppose the waves to be propagated along the chord of the Earth joining the origin to the observing station or parallel to the surface. Calculated on this latter supposition, which seems to be more probable, the velocities of the different waves of the earthquake motion come out approximately the same, irrespective of the arcual distances, those cases, in which epicentral distance is small, say some 30 degrees, being excluded. On the chord supposition, the corresponding velocities come out quite different, according to the distances.

If we denote by V_1, V_2, V_3, V_4, V_5, V_6, V_7, and V_8, the velocities of propagation (supposed parallel to the Earth's surface) of the waves at the commencement of the successive phases of the earthquake motion, their mean values are as follows:

$V_1 = 13.7$ km per sec.
$V_2 = 7.2$ km per sec.
$V_3 = 4.6$ km per sec.
*$V_4 =$ — km per sec.
$V_5 = 3.3$ km per sec.
$V_6 = 2.8$ km per sec.
$V_7 = 2.4$ km per sec.
$V_8 = 2.1$ km per sec.

Now the velocity of propagation of the vibrations at the commencement of the principal portion of a *near* earthquake is 3.3^{km} (or 2 miles) per second, which is the same as V_5 above. Hence it is evident that the vibrations in the third phase of the principal portion are transmitted along the surface of the Earth's crust.

The transit velocity of the vibrations of the first preliminary tremor, namely, V_1, is very great and no known rock has an elastic modulus sufficiently large to propagate with such a high velocity, whether the vibrations be longitudinal or transverse. Hence we must conclude that the waves of the first preliminary tremor are transmitted along some path within the Earth's crust. As, however, the duration of the first preliminary tremor at a given station is very nearly proportional to the arcual distance between the latter and the earthquake origin, it seems likely that the waves of the first preliminary tremor are transmitted parallel to the surface of the Earth and at a probably constant depth below it; the law of the first preliminary tremor, or generally the preliminary tremor, being explained on the supposition that the waves of the first and second preliminary tremors and of the principal portion are all generated simultaneously at the earthquake origin, but are gradually separated from one another as the disturbance spreads from the latter on account of the difference of the transit velocities. The layer, along which the high velocity (V_1) waves are propagated may probably mark the limit beyond which the seismic waves are, on account of certain physical properties of the underlying medium, unable to penetrate; or may be, as Professor NAGAOKA suggests, one of the maximum transit velocity. A very rough calculation, based on the relation of the duration of the first preliminary tremor and the epicentral distance, and on the value to the different velocities, gives 600^{km} or about 400 miles, as the probable depth of the layer along which the vibrations of the first preliminary tremor are propagated.

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*Not definitely known.

It is probable that the waves having velocities V_2 and V_3 are transmitted along layers at some smaller depths within the Earth's crust.

PROPAGATION OF THE SEISMIC MOTION COMPLETELY AROUND THE EARTH. Let T be the observing station and C the earthquake origin. Then there are three sets of motion, which can be distinguished and which we shall denote respectively W_1, W_2 and W_3 waves:

Firstly, the W_1 waves are those propagated from C to T along the shortest path, parallel to the surface, namely along the minor arc;

Secondly, the W_2 waves are those propagated from C in the opposite direction and arriving at T after passing through the antipode of C, namely, along the major arc; and

Thirdly, the W_3 waves are the W_1 waves which are propagated beyond T in the same direction, and again arriving at T, after making one complete circuit of the Earth.

The identification of the W_3 waves is possible only in a very small number of cases; that of the W_2 waves is, however, more definite, being usually characterized by the fact that their period is much slower than those of the preceding vibrations which form the end portion of the W_1 waves.

The average period of the W_2 waves is, with a few exceptions, very uniform and gives a mean value of 20.4 sec., which is identical with the predominating period in the third phase of the principal portion; the period of the W_3 waves is also probably nearly the same as that of the W_2 waves. These facts seem to indicate that the W_2 and W_3 waves are the same as those which constitute the third phase of the principal portion of the earthquake proper.

The time interval between the arrival of the W_1 and of the W_3 waves is 3h. 20m. 46s., this agrees with the time that would be taken by the vibrations in the third phase of the principal portion in making one complete circuit around the Earth, with the velocity of 3.3^{km} per second.

THE SAN FRANCISCO EARTHQUAKE OBSERVED IN TOKIO. As an example of a large distant earthquake observed in Tokio, I may mention the great shock of April 18, last. The time of commencement in Tokio of the earthquake was 5h. 24m. 35s. a.m. (Pacific time;) the total duration of motion being 5 hours. The duration of the first preliminary tremor was 9m. 49s., from which the approximate arcual distance between the origin of the earthquake and the observing place was calculated to be about 5400 miles, and the time of the occurrence at the origin of the shock to be about 5h. 13 m. 5s., A. M. (P. S. T.)

The first displacement of the well-defined horizontal vibration at the commencement of the second preliminary tremor, was directed toward S 27° W.; the counter displacement being directed towards N.E. It will be observed that the directions of these movements were approximately equal to the direction of the great circle joining Tokio with the origin of disturbance. namely S.W. and N.E.

At about 7h. 31m. A. M., (P. S. T.) namely, 2h. 6m. 35s. after the commencement of the disturbance, there began vibrations which correspond to the same earthquake motion propagated along the major arc of the Earth, namely, which traveled from the center in a southeastern direction, through South America, the Atlantic and the Indian Oceans.

As other examples of large earthquakes which disturbed the west or Pacific Coast of the American continent, I may mention the following:

Alaska earthquake on September 3d and 10th, 1899, and on October 9th, 1900.

Central American earthquakes, on April 18th and September 22nd, 1902.

Panama, Colombia and Equador earthquake, on January 31st, 1906.

Now the whole Pacific Coast, which forms one of the most active seismic districts in the world, is frequently visited by earthquakes of different size and intensity. Large destructive earthquakes have, however, a tendency to happen in groups, namely, they occur at different parts of a given region or zone in the course of a few years. Thus, as mentioned above, there were, between September, 1899, and January, 1906, a series of six extensive disturbances which affected the whole west coast from Alaska down to South America, indicating that these earthquakes were of no local character, but that great stresses were going on along the Pacific border, such that the extension of the seismic disturbance to the coast of the United States would have been a most natural event to be expected. The great earthquake of April 18th last, may therefore be regarded as having completed the continuity of the manifestation of the seismic activity along this part of the world. Now an earthquake is caused by the existence of a weak point underground, which, reaching the limit, finally gives rise to a sudden disturbance which forms the source of wave motion propagated through the rock and the soil. A very extensive earthquake, such as that of April 18th, may thus be regarded as having removed a considerable unstability existing in this part of the Earth's crust; those regions most violently shaken becoming seismically the safest place for a certain time interval to come. As a matter of fact, there has been no case in which great earthquakes have originated successively at one and the same center.

The small after shocks which will continue to shake the different portions of the western coast for a few years, are not of a dangerous nature. On the contrary, it is absolutely necessary that these small shocks should occur, as the disturbed Earth's crust settles, by means of these shocks, into the original condition of equilibrium; and even in the case of a future earthquake, after a number of years, the intensity of motion would not be so violent, and it will be an easy task to make architectural and engineering works perfectly earthquake proof.

San Francisco, June 9, 1906.

ECLIPSES OF THE SATELLITES OF SATURN, OCCURRING IN THE YEAR 1906.

By Hermann Struve.

The interesting observations of the eclipses of the satellites of *Saturn*, being of the greatest value for deriving the diameters of the planets, for correcting the elements of the orbits and for conclusions as to the dimensions of the satellites, and some physical questions, it is to be hoped, that the favorable opportunities for observing the eclipses during the present and next year will not be lost. The attention of astronomers, who are in possession of powerful instruments is particularly directed to these phenomena. But in the case of the brighter satellites, *Tethys, Dione, Rhea* and *Titan,* instruments of moderate size also could be employed with success.

In the present year the cycle of eclipses extends over all interior satellites from *Mimas* to *Rhea; Titan* and *Hyperion* will be eclipsed only during the next opposition. To facilitate these observations, I have calculated the approximate times and places of the eclipses for every day from June 1st to the